NASA/TM—2005-214011

Continuous Operation of PEM Regenerative Fuel Cell System for Energy Storage

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November 2005

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Prepared for the
56th International Astronautical Congress
sponsored by the Japan Aerospace Exploration Agency
Fukuoka, Japan, October 17–21, 2005

National Aeronautics and
Space Administration

Glenn Research Center

November 2005

This work was sponsored by the Low Emissions Alternative Power Project of the Vehicle Systems Program at the NASA Glenn Research Center.

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Abstract

NASA Glenn Research Center (NASA Glenn) has recently demonstrated a Polymer Electrolyte Membrane (PEM) based regenerative fuel cell system (RFCS) that operated for five contiguous back-to-back 24-hour charge/discharge cycles over a period of 120 hours. The system operated continuously at full rated power with no significant reactant loss, breakdowns, or degradations from June 26 through July 1, 2005. It demonstrated a closed loop solar energy storage system over repeated day/night cycles that absorbed solar electrical power profiles of 0 to 15 kWe and stored the energy as pressurized hydrogen and oxygen gas in charge mode, then delivered steady 4.5 to 5 kWe electrical power with product water during discharge mode. Fuel cell efficiency, electrolyzer efficiency as well as system round trip efficiency were determined. Individual cell performance and the spread of cell voltages within the electrochemical stacks were documented. The amount of waste heat dissipated from the RFCS was also reported. The RFCS demonstrated fully closed cycle operation without venting or purging thereby conserving reactant masses involved in the electrochemical processes. Smooth transitions between the fuel cell mode and electrolyzer mode were repeatedly accomplished. The RFCS is applicable to NASA's lunar and planetary surface solar power needs, providing lightweight energy storage for any multi-kWe application where an environmentally sealed system is required.

Introduction

Multi-kilowatt electrical power system technology is required for NASA’s future lunar base, Mars exploration and 100-day HALE Solar Aircraft. With a photovoltaic array for power generation, there needs to be an electrical energy storage system to supply the power demand during the sun eclipsed periods. A RFCS consisting of a dedicated fuel cell stack and electrolysis stack has been shown to be a strong candidate for solar energy storage in a wide variety of environments wherever the sun/shade extends into periods of several hours or beyond.

To evaluate the regenerative fuel cell technology for a solar plane, NASA Glenn built a RFCS breadboard as shown in Figure 1 under the Environmental Research Aircraft and Sensor Technology (ERAST) program and it became fully operational in 2003. It was capable of integrating different fuel cell and electrolysis stacks and running them in a closed cycle system where nothing enters or leaves the system other than electrical power and heat (Ref. 1). The initial operation of the breadboard was discrete in that the electrolyzer and the fuel cell were run on separate days to gain insight to the system

Figure 1.—PEM Regenerative Fuel Cell System (RFCS) breadboard at GRC.

characteristics and to determine the stack performance (Ref. 2). The objective of the current continuous test was to demonstrate operation of the RFCS breadboard as an energy storage system through multiple back-to-back charge/discharge cycles.

Background

In energy storage via fuel cell/electrolysis, there have been two distinctive types considered for aerospace application based on the use of either alkaline or acid electrolyte. The alkaline system was considered first by NASA because of the high current densities that could be achieved. An example of the alkaline electrolyte RFCS is the system discussed by Chang et al. (Ref. 3). An alkaline RFCS breadboard incorporating a Shuttle fuel cell power plant and a water electrolysis subsystem was operated at 2-kWe level for a total of 41 cycles simulating a low earth orbit (Ref. 4). Because of the inherent limitation in withstanding internal delta pressure transient and other operational and safety concerns such as containment of liquid electrolyte, the alkaline RFCS was not further pursued. The acid based fuel cells using PEM technology experienced significant improvement in the 1990s due to their potential terrestrial application. The PEM electrolyzer also established itself as an industrial on-site hydrogen generator. Based on these development efforts, light weight PEM RFCS was considered for the solar aircraft under

NASA's ERAST program. NASA Glenn procured PEM fuel cell stacks and electrolysis stacks under ERAST program and later under the Low Emissions Alternative Power (LEAP) program. The ERAST/LEAP fuel cell stacks were designed specifically to operate with hydrogen and oxygen as fuel and oxidant, respectively. The electrolyzers were capable of generating hydrogen and oxygen up to 400 psig. The hardware heritage from ERAST has continued to the present RFCS. The stacks used in the current test were fuel cell model G4FC64-002 rated at 4.8 kWe and Electrolyzer model G4EZ60-003 rated at 15 kWe, both manufactured by Lynntech, Inc.

System Operation

Energy storage test preparations began June 10, 2005. The fuel cell oxygen phase separator in the RFCS was charged with 26 liters of de-ionized water with conductivity of 0.8 micro-siemens/cm. It served as water reservoir for electrolysis to pressurize the gas storage tanks from 70 to 400 psig. The fuel cell hydrogen phase separator and the separators on the electrolyzer side contained residual water to satisfy the low level limit for the primary control circuit of the RFCS. The gas storage tanks were evacuated earlier and had 70-psig worth of reactant gases from a previous electrolysis run. The gas samples were analyzed indicating a purity level of 99.994 percent for hydrogen and 99.843 percent for oxygen. After the stacks were installed in the RFCS rig, the entire system, except for the gas storage tanks which were isolated by valves, was evacuated through access ports to a vacuum level better than 4 mbar using a vacuum pump. The forward pressure regulators in the fuel cell inlets were preset to 65 psig. The power supply simulating solar array, the electronic load simulating power consumption, and chillers simulating heat sink were turned on.

The day-cycle program with more than a dozen control loops and their default parameters was loaded into the master and slave PC-based controllers. In addition, the electrolyzer current profile corresponding to a 16-hr day condition with a maximum current of 150 A was stored in the software. The fuel cell current ramping rules for the fuzzy logic controller were defined to reach maximum current draw of 100 A without cell drop-offs. The output current then stayed at this level until tank pressure lowered to 70 psig at which time the system switched to electrolyzer operation.

From June 21 through June 24, 2005, the RFCS was run on a daily basis during regular shift working hours with one day at maximum-current charging and the next day at maximum-current discharging for two cycles. The continuous test began at 5 p.m. on June 26 and lasted until 5 p.m. on July 1 completing a total of 5 cycles. Throughout the continuous test, operators manned the control room to respond to the software prompting during mode transitions and to initiate flow surge occasionally during fuel cell operation.

Results and Discussion

The input power and output power during the 5-cycle run are shown in Figure 2. The input energy and output energy integrated over the same time period were 478.5 and 191.5 kWh, respectively. The round trip efficiency was determined to be 40.03 percent without considering parasitic power. The electrolyzer efficiency varied between 98 and 87 percent depending on the current level. The fuel cell efficiency was approximately 47 percent at constant current of 100 A, which indicated that the fuel cell was the major contributor to the system inefficiency. These efficiency numbers were calculated using the average cell voltage and did not include the Coulombic efficiency.

The fuel cell and electrolyzer stack voltage and current are presented in Figure 3. The fuel cell stack voltage showed an open circuit condition immediately after removing the current draw. Because the fuel cell stack was isolated from the rest of the system during the charge cycle, the fuel cell stack voltage and pressure continued to drop due to recombination of trapped hydrogen and oxygen. The electrolyzer stack, on the other hand, remained connected to the gas storage tanks during the discharge cycle. As a result, the stack voltage level climbed up as the tank pressure lowered. To show individual cell voltage spread within the stack, the maximum and minimum cell voltage are plotted for the fuel cell and electrolyzer in

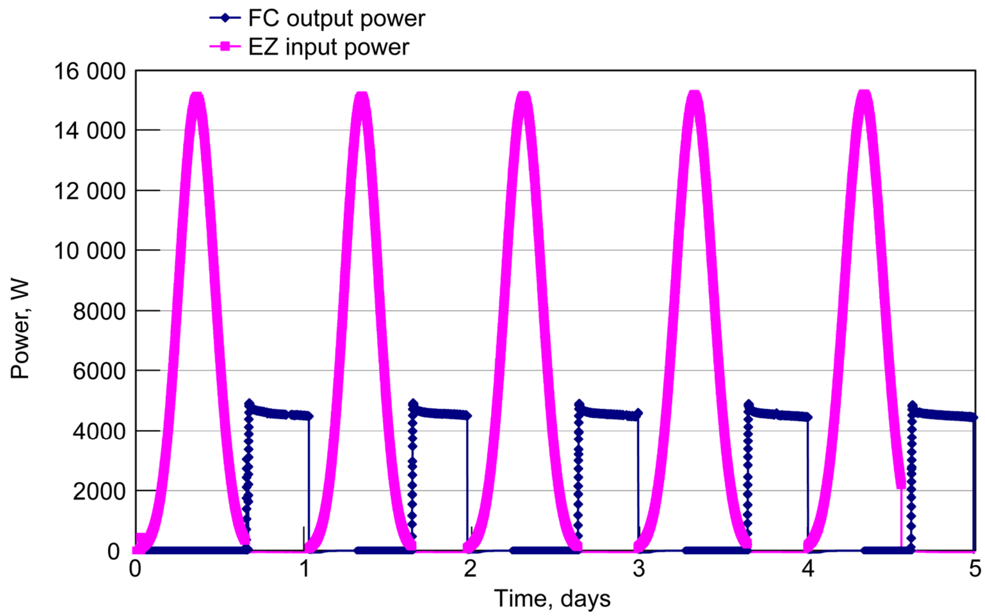

Figure 2.—Input and output power of RFCS versus time.

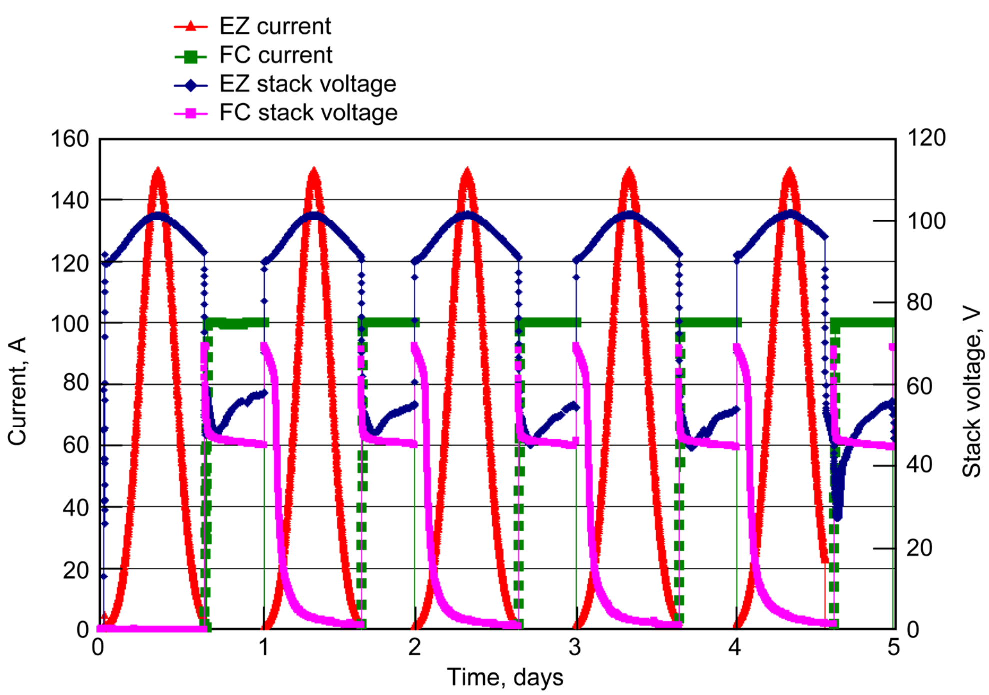

Figure 3.—Fuel cell and electrolyzer stack current and voltage versus time.

Figure 4. The electrolyzer cell voltage spread increased with current and reached 69 mV at 150 A. This spread was much lower than that of the fuel cell stack, which was approximately 110 mV at the end of each discharge cycle. The individual cell performance of the fuel cell stack right before the end of the test (100 A stack current) is captured in Figure 5. The cells in the middle of the stack appeared to have lower voltage levels. A typical electrolyzer cell performance at maximum current is shown in Figure 6. More uniform cell voltages are evident compared with fuel cell stack.

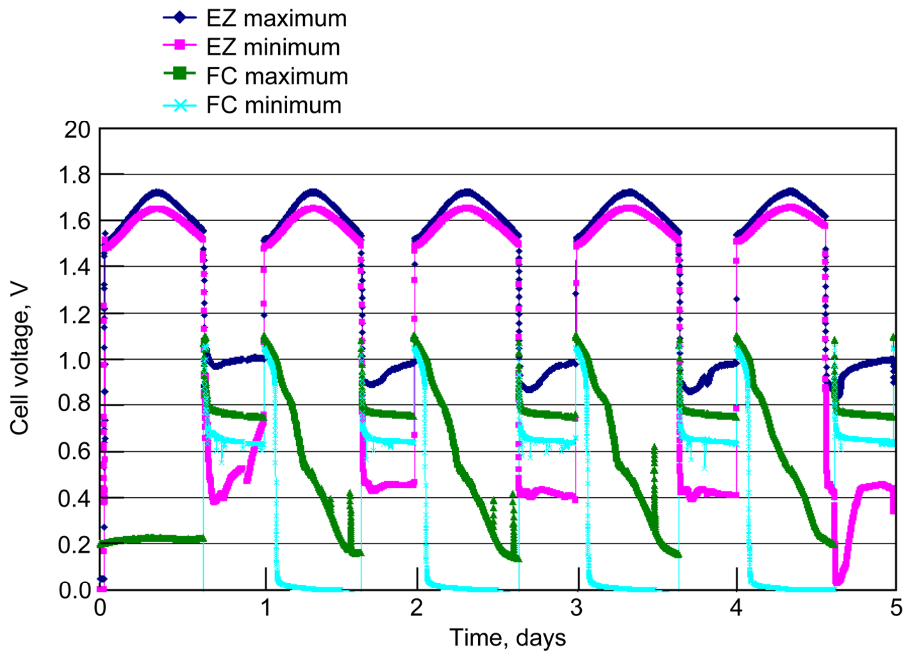

Figure 4.—Fuel cell and electrolyzer maximum and minimum cell voltage.

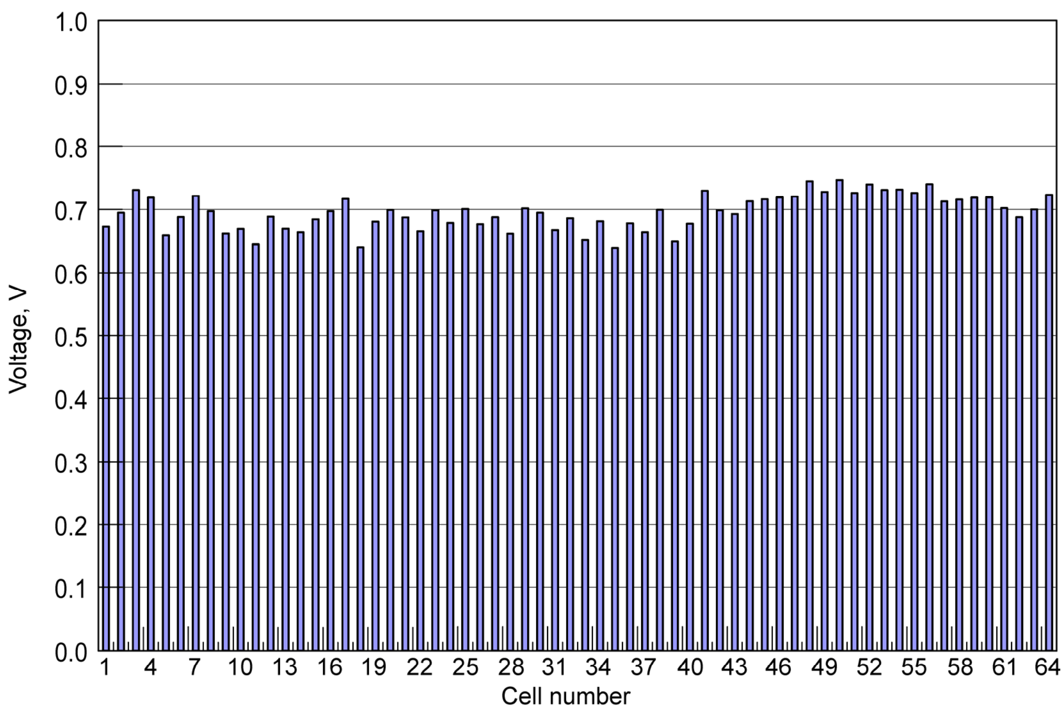

Figure 5.—Fuel cell individual cell performance at 100 A, 65 psig, and 135 °F.

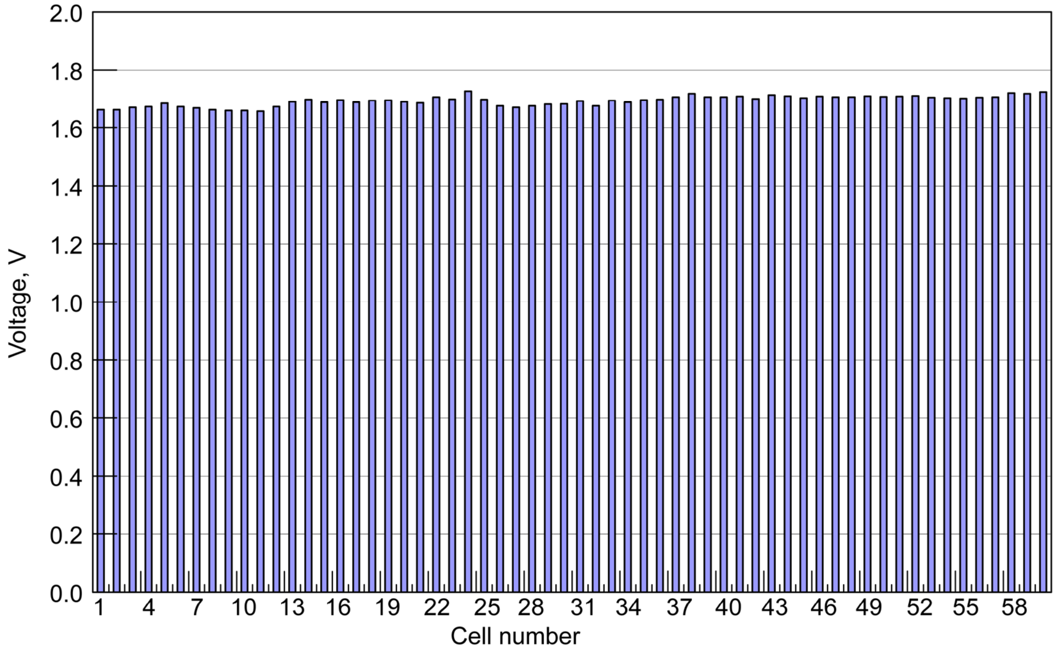

Figure 6.—Electrolyzer individual cell performance at 150 A, 245 psig, and 140 °F.

The overall system mass balance is depicted in Figure 7 where the hydrogen and oxygen tank pressure and the quantity of water in the reservoir were plotted over the entire test time. The cyclic nature of the amount of gases and water was indicative of a totally closed system. There was no need to vent any gas impurity from the system to maintain fuel cell operation or to purge the system with nitrogen to safe the system during the test even though such provisions were available. A comparison of water inventory before and after the test showed less than 1 percent loss. The most likely cause of loss of water was due to permeation of product gases to the ambient through the electrolysis stack during periods of high operating pressures.

The inefficiency of the fuel cell stack discussed previously appeared as waste heat dissipated to the heat sink. The fuel cell coolant inlet and outlet temperatures in the last cycle are plotted in Figure 8. Also included in the plot were the calculated waste heat based on the temperature rise and coolant flow rate. The amount of waste heat thus calculated accounted for the fuel cell inefficiency based on the higher heating value. This result was consistent with the fact that the product water was removed from the fuel cell stack primarily as liquid water not as water vapor. A similar plot for the electrolyzer is shown in Figure 9. The amount of waste heat generally followed the current profile and was appreciably lower than that of the fuel cell because of better efficiency. It should be pointed out that the fuel cell operating temperature was well controlled by maintaining constant coolant exit temperature at 135 °F whereas the electrolyzer had difficulties controlling constant coolant exit temperature during periods of low power input level when the concomitant waste heat generation was reduced. A solution to this problem is to provide better thermal insulation of the electrolysis stack.

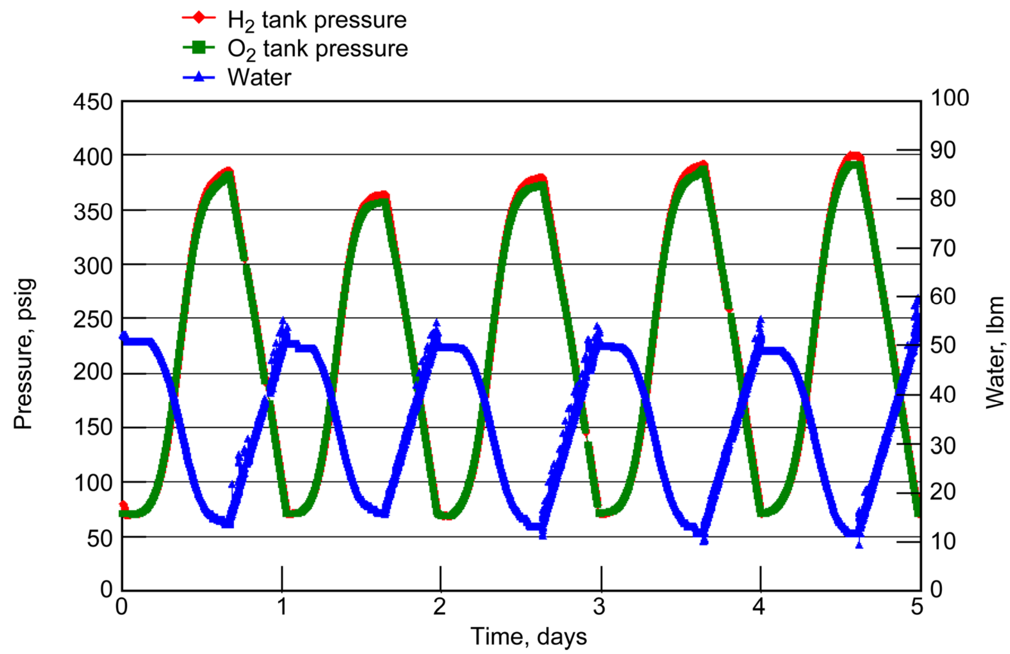

Figure 7.—RFCS gas and water material balance.

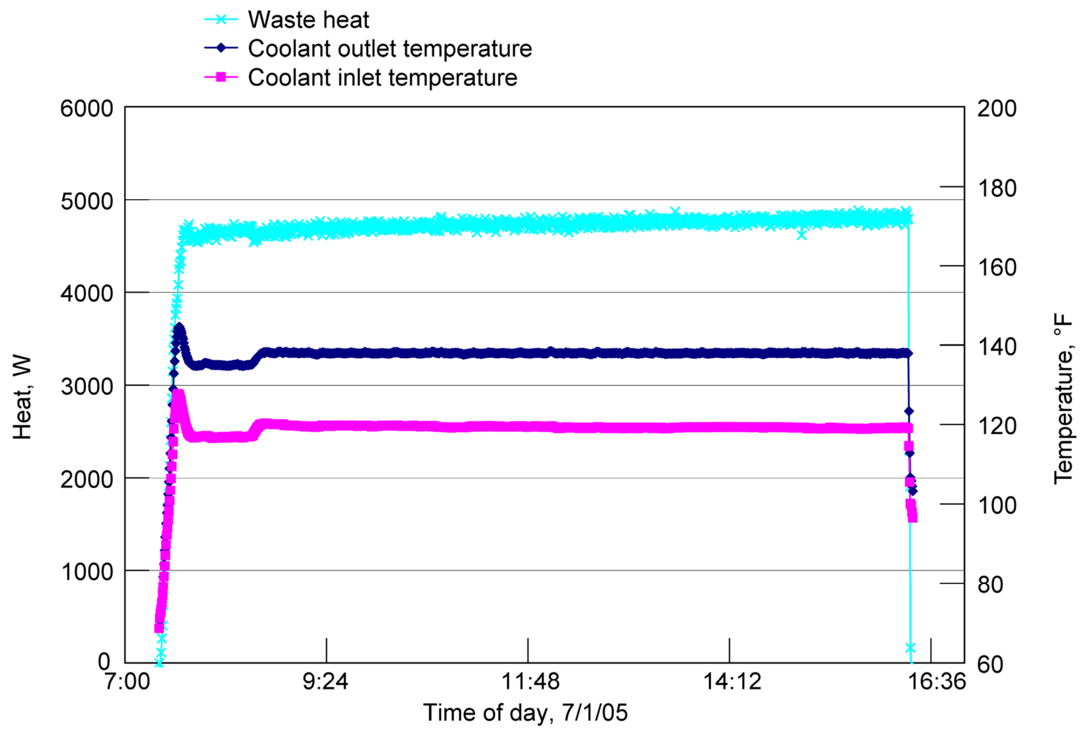

Figure 8.—Fuel cell thermal control performance in 5th cycle.

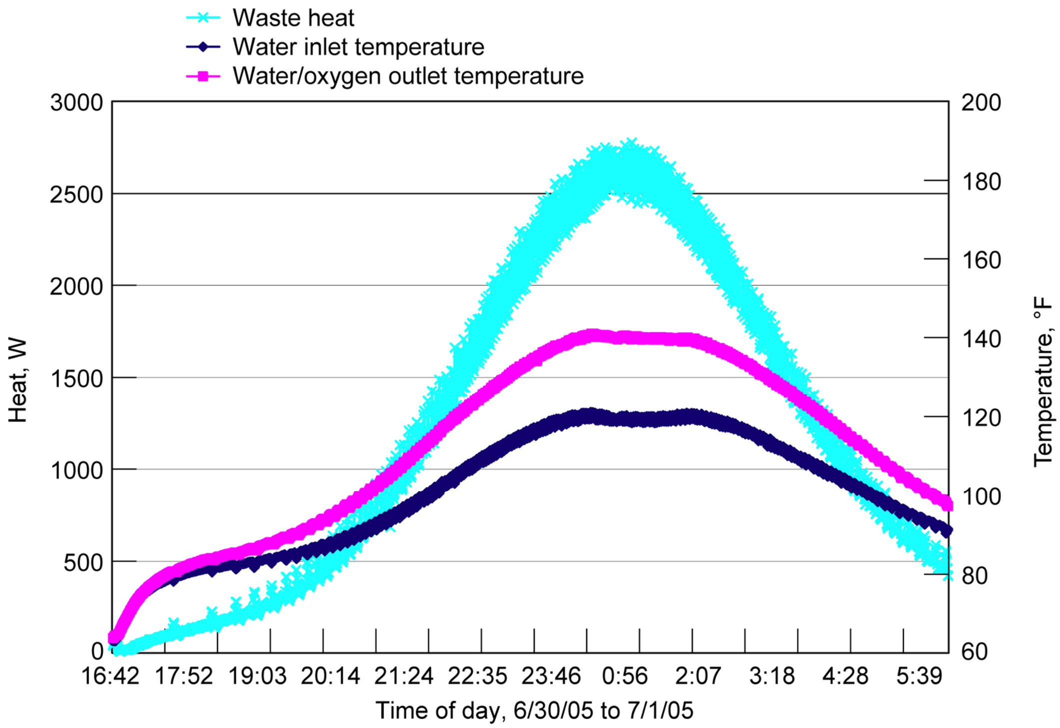

Figure 9.—Electrolyzer thermal control performance in 5th cycle.

Conclusions

The NASA Glenn PEM RFCS breadboard demonstrated contiguous five-cycle operation. At the end of five-day test, the system was capable of running additional cycles. There was minimum human intervention in operating the breadboard with smooth transitions between the fuel cell mode and the electrolyzer mode. Based on this experience, it may be concluded that the PEM RFCS has matured to a NASA Technology Readiness Level (TRL) of approximately 5 or better.

The existing fuel cell stack will be replaced with more advanced stacks to achieve higher system efficiency while operating at pressures close to 40 psig. Light weight gas recirculation pumps will be incorporated into the breadboard to reduce system weight projection. Future plan also calls for fully autonomous operation and demonstration of tens of charge/discharge cycles.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 2005	Technical Memorandum

4. TITLE AND SUBTITLE

Continuous Operation of PEM Regenerative Fuel Cell System for Energy Storage

5. FUNDING NUMBERS

WBS–22–066–20–04

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–15328

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2005-214011

11. SUPPLEMENTARY NOTES

Prepared for the 56th International Astronautical Congress sponsored by the Japan Aerospace Exploration Agency, Fukuoka, Japan, October 17–21, 2005. Bei-jiann Chang, Christopher P. Garcia, and Donald W. Johnson, QSS Group, Inc., 21000 Brookpark Road, Cleveland, Ohio 44135; David J. Bents and Vincent J. Scullin, NASA Glenn Research Center; and Ian J. Jakupca, Analex Corporation, 1100 Apollo Drive, Brook Park, Ohio 44142. Responsible person, Bei-jiann Chang, organization code DRH, 216–433–5095.

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13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS

Regenerative fuel cells; Energy storage

15. NUMBER OF PAGES

14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	